Artificial light at night as an environmental pollutant: An integrative approach across taxa, biological functions, and scientific disciplines

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Introduction

The world is becoming every day more urbanized. An increasing number of people move into urban areas, and consequently these increase in area to consume rural and natural land [1]. Among the numerous changes that accompany urban sprawl, artificial light at night (ALAN) is one of the most immediate and evident [2,3]. From a variety of anthropogenic sources, artificial light is introduced at times (the night) and in places where it does not naturally occur [3]. The characteristics of the introduced light sources are also very different to natural light. Artificial light is often of an intensity higher than naturally occurring light at night, for instance due to moon or starlight [4]. Furthermore, the spectral properties of artificial light are often enriched of a specific wavelength, in particular the blue portion of the spectrum [4,5]. ALAN is increasing at a steady pace globally (6 % per annum) [3], but with tremendous spatial variation (from negative trends to positive changes of up to 20 % per annum) [6,7]. Although the proportion of the Earth's surface covered by urban land is below 5 % [1], between 10 and 20 % of the global land experiences some degree of ALAN [8]. This is mainly due to the skyglow effect [8], but further because artificial light is used also outside of urban areas, for instance on roads connecting different cities, or in remote industrial installations [3].

A key question for biologists is whether the alteration of natural lightscapes by ALAN has any consequence for the organisms that inhabit light polluted areas, including humans [4,5,9]. Species have evolved over millions of years in habitats where daily, lunar, and seasonal cycles are dominant sources of environmental variation are driven by changes in light regimes [10,11]. Organisms have thus developed specific molecular, physiological and behavioural adaptations to such rhythms of life [10,11]. How are these organismal adaptations coping with a light polluted world? How do responses at the individual level scale up to influence, populations, communities, and ultimately ecosystems? Importantly, can we identify lighting practices that minimise the environmental impacts of ALAN? In recent years the scientific interest in such questions, and more generally in the biological impacts of ALAN, has bloomed. This has led to an explosion of research papers that have investigated a plethora of effects of ALAN on individual organisms, species and communities. This special issue was conceived to illustrate the breadth of research questions that the study of light pollution has focused on in recent years. Moreover, we aimed at highlighting recent developments and challenges in this field. We focus on three of these. First, the need to investigate the ecological effects of ALAN in a diverse array of species representing the extraordinary diversity of life, from microbes to plants, from invertebrates to all vertebrate classes. Second, the need for studies at different levels of biological organisation, from molecules to physiology, behaviour, species, and communities. Third, the need to establish intensity and spectral-dependent effects of ALAN, with the ultimate goal to produce relatively simple guidelines that would inform policy-makers and produce tangible impacts on the way that lighting systems are designed, produced and ultimately installed. We believe that to meet these challenges an integrative and multidisciplinary approach is needed.

The effects of ALAN on different species

The papers included in this special issue represent outstanding taxonomic breadth. From insects to mammals, several animal classes, both invertebrate and vertebrate, are represented. McLay and coauthors investigated effects of ALAN on reproduction and physiology in *Drosophila* [12]. Insects were also the focus of Donners and collaborators, who modelled the attraction of several insect orders to light sources of different colours, allowing the application of light sources that reduce insect attraction [13]. Within the invertebrate group, van Grunsven and colleagues shift to Molluscs, and in particular to slugs, and show how this group actually benefits from nocturnal illumination, likely via reduced predation risk and increased foraging success [14]. In vertebrates, the greatest majority of studies that looked at the impact of light pollution on wildlife concerned birds and mammals. This is reflected also in our special issue. In birds, Great Tits (*Parus major*) have been and continue to be a model organism. Three of our papers studied this species. De Jong and collaborators examined if and how the rate of extra-pair paternity was affected by lights of different colours [15]. Dominoni and coauthors assessed dose-dependent responses of the reproductive system [16]. Raap et al asked whether roosting in cavities may limit the effects of light pollution on sleep [17]. Other passerine bird species included in this issue are the Indian Weaver Bird (*Ploceus philippinus*) and the Zebra finch (*Taeniopygia guttata*). Through captive experiments, Kumar and collaborators demonstrated that light at night can alter daylength perception in weawer birds [18], whereas Alaasam et al revealed that cool light temperatures disrupt sleep and increase corticosterone levels in zebra finches [19]. Last but not least among birds, Little Penguins *(Eudyptula minor)* were studied by Rodriguez and colleagues, which showed increased used of light areas during colony attendance, probably because light enhances vision at night and thereby reduces energy expenditure and predation risk [20]. Two different mammal species are also covered by our special issue. Spoesltra and others reveal that the choice of Daubenton's bats to commute through tunnels was unaffected by whether such tunnels were illuminated or not [21]. Dimovski and Robert report spectral-dependent suppression of melatonin levels, as well as changes in oxidative status, in Tammar wallabies (*Macropus eugenii*).

While such an impressive line-up of studies illustrates the taxonomic and geographic breadth of the current research on the ecological effects of light pollution, some groups remain understudied. For instance, we still have limited understanding of the effects of ALAN on plant species, as highlighted in a recent review [22]. Being primary producers as well as photosynthetic organisms, plants play a key role in the trophic chain and are highly sensitive to changes in light regimes, calling for more research in this field. Similarly, studies on phytoplankton are also limited but extremely needed to better understand the impact of light pollution on aquatic ecosystems [23,24]. Some vertebrate groups such as fish, amphibians and reptiles are also underrepresented in the literature, at least when compared to the amount of information already available on birds and mammals responses to ALAN (but see [25–27]). We also want to stress that besides generalizing across taxa, more studies are also needed within the same taxonomic group but focusing on different species. Indeed, species that are closely related might very well different in their sensitivity to light, as studies in moths and birds have suggested [28,29].

The effects of ALAN at different levels of biological organisation

A major aim of our special issue was to reveal the multitude of molecular, physiological and behavioural mechanisms that light pollution can affect. At the molecular and physiological level, these and previous papers have shown that ALAN can alter patterns of gene expression [16,30–32], hormone secretion [19,33–35], body temperature [18], energy expenditure [36], immune function [37–39], and oxidative stress [5,12]. Given such extensive changes in the underlying physiology, it comes with no surprise that an impressive array of behavioural effects of ALAN has been revealed. Mating [12,40–43], singing [29,44], sleep [45], mood- and anxiety-related behaviours [46], habitat selection [47], predation [47], migratory movements [48], commuting movements [49], these are some of the behavioural categories affected by ALAN. Some of these are reviewed by Russart and Nelson [50] in our special issue. Moreover, the special issue also includes a timely perspective from Auselbrook and collaborators on the impacts of ALAN on sleep [51]. Although evidence is accumulating for light pollution to alter sleep behaviour and nocturnal rest, the physiological basis for such changes is unknown. Advances in biologging of sleep [52] offer exciting perspectives, especially if integrated with on-board recording of activity and light exposure [53].

As knowledge of the individual responses to ALAN at different levels of biological organisation is accumulating, so is the evidence for impacts at higher levels, such as population dynamics, community composition, and ecosystem function. Sanders and Gaston open our special issue with a review on the effects of light pollution on ecological communities [54]. One of the evident impacts of ALAN is the disruption of biological timing, which can differ in the extent and nature between different species. This may lead to an alteration of interspecific interactions [55,56], population dynamics [57] and ultimately community composition [54,58–61]. Such cascading effects may be more common than previously thought, and may also underline trends in species abundance. For instance, light pollution has recently been suggested as an important threat to pollination [60] and one of the causes of the rapid, dramatic decline in insect biomass observed in recent decades [62]. However, how responses at the individual level drive changes in population dynamics and communities is still a knowledge gap and constitutes an important research challenge for this field. Indeed, although trends in species abundance and ecosystem services may be the main functional output that conservation biologists and policy-makers focus on, we argue that without a knowledge of the mechanisms generating such trends it will be impossible to design evidence-based conservation plans.

Applying fundamental knowledge to policy-making and conservation

Artificial light at night is the perfect example of a type of environmental pollution for which concrete management plans can be designed in order to reduce or completely eliminate its impact on species and ecosystems. Literature on this particular topic is growing and new evidence is constantly added [63,64]. The first obvious mitigation measure should be eliminating any illumination when this is not strictly needed. When not possible, light emissions from streetlamps should be shielded so that light is only directed to the ground and not to the sky. Moreover, given the clear dose-dependent effects that light has on many behavioural and physiological responses (see for instance [16] in the special issue, as well as [34,65]), artificial light should be tuned to the intensity necessary to render an area visible to the human eye, but any excess lighting should be avoided.

A more complicated issue is that of the spectral composition of light. It's becoming increasingly evident that the colour of the emitted light is important to determine whether or not, and the degree to which, a species is affected by ALAN. Thus far, mounting evidence seems to suggest that short wavelengths in the visible spectrum can cause the strongest effects. For instance, suppression of nocturnal melatonin by ALAN has been found to be highest under blue light across taxa, from insects to fish, birds and mammals, including humans [27,66–68]. Other traits show similar strong responses to nocturnal blue light [69–71]. Three articles in our special issue confirmed this evidence for insect phototaxis [13], corticosterone levels in birds [19] and oxidative status in wallabies [72]. Thus, it seems that white light, which contains a high proportion of blue wavelengths and is one of the most common light sources used for nocturnal illumination, should be avoided. This has been become particularly because of the ongoing switch to LED lighting. Such a switch, motivated by mostly economic reasons, has led to the widespread replacement of incandescent and low pressure sodium vapour lamps (rich in long wavelengths but less efficient) with cool white LEDs. Such conversion has been suggested to be associated with recent increases in the radiance and spatial extent of light pollution, especially in developed countries [73]. However, more research on this topic is needed, because certain species and/or specific biological functions might be more sensitive to wavelengths other than blue light. For instance, magnetoreception in birds is mostly sensitive to red light [74], and indeed red light has been associated with disruption of navigation in seabirds [75]. Thus, caution needs to be taken when choosing a particular colour for a new light installation.

Conclusion

The papers of this special issue demonstrate that an integrative approach across taxa, biological functions, and scientific disciplines is needed in order to fully appreciate the effects of light pollution on individual, species, and ecological communities. Moreover, such an integrative approach will help us to develop a common, mechanistic framework to improve the design future studies, and identify knowledge gaps. This will also promote collaboration between researchers studying different species or coming from different scientific backgrounds, something that is particularly needed in this field, as the study of light pollution brings together chronobiologists, ecologists, conservationists, physicists, engineers, businesses, and policy-makers. Our ultimate goal should be to reconcile the need for artificial light in our society with the need to preserve our health as well as the health of the ecosystems we live in. We thus believe that this special issue comes at a very appropriate time.

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